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Tree Canopy Cover and Potential in Portland, OR: a Spatial Analysis of the Urban Forest and Capacity for Growth

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Tree Canopy Cover and Potential in Portland, OR:

A Spatial Analysis of the Urban Forest and Capacity for Growth

by

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Abstract

Urban forests have positive impacts on human and ecosystem health, reduce stress on aging stormwater infrastructure, increase property values, and reduce energy consumption. The scale of these benefits ranges from the hyper-local to the global. While the benefits of urban forests can extend well beyond the boundaries of cities, they often do not reach all residents of the city equally. Urban forest policies do not adequately address environmental equity or employ planting strategies with knowledge of the social and political factors that determine the spatial variations of tree canopy extent in cities. Chapter I analyzes the determinants of current canopy extent in Portland, OR using spatial regression analysis. Chapter II uses current landcover datasets to identify potential planting opportunities. Results of spatial regression show that income and education level are significantly positively linked to tree canopy, while sewer pipe density, an indicator of development, is negatively associated with canopy. The majority of tree canopy and potential in the city occurs on private, residential lands. Distribution of canopy potential is not even, with greater amounts in north and outer east side areas. Findings presented here will inform efforts to expand tree canopy in Portland in a manner that is spatially explicit and based on Portland's unique demographics, land use assemblage, and development policies.

Acknowledgements

Thanks to my thesis committee, Heejun Chang, Geoffrey Duh, and Andrés Holz, for their assistance with developing research methods and design, and for their input on this final product. Thanks to the committee chair, especially, for his periodic reminders and encouragement over the years that helped push this project forward. Thanks also to the Portland Parks & Recreation Urban Forestry Division for their support of this research, and to Angie DiSalvo for helping with concept development. Lastly, sincere and profound thanks to my wife Amanda, whose support made this project, and the many hours of work it took to complete, possible.

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I. Introduction

More than half of the world's population now lives, works, and recreates in cities (United Nations DSEA Population Division 2018). Most human interaction with the natural world, therefore, takes place in these unique, human-dominated environments. As a result, urban ecosystems have received increased attention from researchers in both the social and biophysical sciences (Alberti 2010; Pickett et al. 2011). Key to this work has been an acknowledgement of the coupled dynamics of human institutions and the natural processes at work in urbanized areas (Grimm et al. 2000; Liu et al. 2007; Ostrom 2009; Cook, Hall, and Larson 2012; Groffman et al. 2017). While there exists ample evidence that shifts to urban land uses result in degraded terrestrial and aquatic ecosystems (Paul and Meyer 2001; Foley et al. 2005; Walsh et al. 2005; Janke, Finlay, and Hobbie 2017), research has also shown the potential to mitigate these impacts through the use of best management practices such as green infrastructure (Hager et al. 2013), including the expansion of urban forests.

Many studies have found positive links between urban forests and a variety of human and environmental factors, including air quality (Escobedo and Nowak 2009; Rao et al. 2014), carbon sequestration (Nowak et al. 2013), reduced stormwater volume (Xiao et al. 1998; Berland et al. 2017), urban heat island mitigation (Akbari, Pomerantz, and Taha 2001; U.S. Environmental Protection Agency 2008), energy savings (Akbari et al. 1997; Sawka et al. 2013; Wang et al. 2016), increased property values (Tyrväinen 1997; Mansfield et al. 2005; Donovan and Butry 2010), and human health outcomes (Lovasi et al. 2008; Donovan et al. 2013). In acknowledgement of these, cities around the world have engaged in large-scale urban reforestation efforts aimed at achieving greater tree canopy extent or stem-count goals. Methods of setting these goals vary widely, as local climate and land cover assemblages, as well as social and political factors, limit the usefulness of generalized recommendations. In recent years, attempts at setting canopy goals based on estimates of *potential canopy*—how much canopy a city's existing pattern of land use can support—have been developed as a means to justify large-scale planting efforts and canopy goals (Grove et al. 2006; Mcpherson et al. 2008; Morani et al. 2011; City of Portland 2018). This approach is promising, as it is specific to local land use assemblages and climate conditions as well as offering a guide for managers in setting priorities for management and expansion of the urban forest.

Goals for tree canopy in Portland have been set by Portland Parks and Recreation in both the *Urban Forest Management Plan* (City of Portland 2004) and *Canopy Report* (City of Portland 2007). The 2004 plan sets canopy targets for five individual Urban Land Environments (ULEs), which are groupings of zoning and land use: residential; commercial/industrial/institutional; natural areas and stream corridors; transportation corridors and rights-of-way; and developed parks and open spaces. The 2007 plan calls for a city-wide canopy goal of 33.3%, regardless of ULE. The latter study used an estimate of local tree canopy (26% in 2002), as well as research from outside of the city to set a goal of 33.3% canopy, and in Portland's *Climate Action Plan* (City of Portland 2009) a date of 2030 was set for achieving this coverage. While both the 2004 and 2007 reports mention Poracsky and Lackner's 2004 study of Portland's urban forest canopy, neither accepts their (much higher) recommendations for canopy goals, which use the 75th percentile canopy coverages of ULEs as a target (Poracsky and Lackner 2004). This points to a disconnect between forest policy, in part guided by outside organizations, and local research.

The goal of this study is to analyze the spatial patterns of existing and potential tree canopy and what factors help explain such patterns in Portland, OR. Studies of potential canopy in other cities have demonstrated that the distribution of planting opportunity is not equal across urban areas. However, few seek to explain why this pattern exists, and fewer still offer management recommendations that go beyond reporting the canopy extent for given land uses or administrative boundaries. A small but convincing body of research exists that links the inequitable spatial distribution of urban forests and their benefits to income, race, and housing characteristics (Perkins, Heynen, and Wilson 2004; Landry and Chakraborty 2009; Schwarz et al. 2015; Locke et al. 2016). Portland has attempted to utilize what is known generally about environmental equity in urban forestry to its own planting goals. The two primary vision documents for the city, the *Climate Action Plan* and the *Comprehensive Plan* (City of Portland 2016) each explicitly link increased canopy to goals of decreased carbon emissions and greater social equity and cite Portland's 33.3% target as a method of achieving those goals (albeit, on a different timeline; the *Comprehensive Plan* sets the target year as 2035). Additionally, the *Urban Forest Action Plan* (City of Portland 2007) specifically instructs city bureaus involved in tree planting to target efforts in known low-canopy and low-income neighborhoods.

This again substitutes outside research (in this case regarding equity and urban forests) for studies specific to Portland regarding the correlation between socioeconomic variables and tree canopy. While the city has chosen the neighborhood scale to define low canopy areas, a more spatially explicit, fine-scaled analysis of the pattern of existing canopy, paired with a realistic estimation of where canopy expansion can occur, will serve as an effective tool for creating canopy goals that are based on Portland's unique land use composition and will equitably distribute the benefits that go along with increased canopy. With this in mind, this research will answer the following questions:

1. What are the determinants of access to tree canopy cover and its benefits in Portland, OR and how does that compare to what has been found in other cities?
2. What is the distribution of canopy potential, or room to expand tree canopy cover in Portland, and what is the value of ecosystem services that such expansion would create?

II. Determinants of Canopy Access in Portland, OR

1. Introduction

Environmental justice activists and academics have traditionally been interested in the disproportionate vulnerability of low-income and minority communities to environmental hazards (United Church of Christ 1987; Cutter 1995; Boer et al. 1997; Gamper-Rabindran and Timmins 2011). In recent years, there has been a broadened focus within the literature to include access to environmental amenities, such as clean air, access to nature, or public parks (Zhou and Kim 2013; Frey 2017). The ecosystem services framework allows researchers and policymakers to better quantify the value of these amenities, further enabling research into which communities benefit most from a city's natural infrastructure, including trees.

The benefits of tree urban tree canopy cover are well documented. From increased mental and physical health outcomes and economic activity to improved environmental conditions and reduced stress on sewer and transportation infrastructure, urban trees are singular in their ability to meet many needs of a city or region, at a relatively low monetary cost. Previous studies in U.S. cities have found the ratio of ecosystem services to management costs for urban trees to be anywhere from 1:1 to 3.6:1 (Vargas et al. 2006; City of Portland 2007). For this reason, expanding tree canopy in cities is seen as an important tool for improving the lives of residents, evident from numerous "Million Trees" initiatives in the past decade from Los Angeles (Million Trees LA 2009) and New York (Million Trees NYC 2015) to Beijing (China Daily 2018). These and other tree planting campaigns are also seen as a vehicle for undoing existing environmental inequities that result from historic patterns of land use, disinvestment in minority communities, or proximity to environmental hazards (Lovasi et al. 2008). This has led to a need for greater understanding of existing patterns of access to the benefits of urban trees. As such, characterizing inequities in the distribution of tree canopy cover is a topic of increasing popularity within environmental justice and urban forest-related literature, with many case studies from cities around the world (see Table 2.1, below).

Table 2.1: Review of selected studies on relationships between tree canopy cover and socioeconomic explanatory variables. Positive (+) or negative (-) relationships found by each study are denoted.

Author	Year	Study area	Spatial unit	Relationship between canopy cover and explanatory variables
Iverson and Cook	2000	Chicago, USA metropolitan area	County	Median income (+)
Pedlowski et al.	2002	Rio de Janeiro, BRA	Neighborhood	Land value (+)
Heynen and Lindsey	2003	Indiana, USA (multiple cities)	Census designated places	Housing age (+), education (+)
Perkins, Heynen, and Wilson	2004	Milwaukee, USA	Census tract	Rentership (-), median income (+)
Landry and Chakraborty	2009	Tampa, USA	Census block group	Home ownership (+), median income (+), percent black (-), percent Hispanic (-)
Flocks et al.	2011	Miami, USA	Census block group	Percent black (-), percent Hispanic (-), percent white (+)
Pham et al.	2012	Montreal, CAN	City block	Housing age (-), low-income populations (-), population density (-)
Conway and Bourne	2013	Ontario, CAN (multiple cities)	Dissemination area (neighborhood)	Housing age (+), Percent white (+)
Cowett	2014	Providence, USA	Census block group	Median income (+), education (+)
Shanahan et al.	2014	Brisbane, AUS	Neighborhood	Economic advantage (+)
Schwarz et al.	2015	Multiple cities, USA	Census block group	Median income (+), percent black (-)
Locke et al.	2016	Philadelphia, USA	Census block group	Population density (-)
Greene	2018	Toronto, CAN	Census tract	Median income (+)

Portland's urban forest is the product of 150 years of human management. Shortly after European-American settlement began in the middle 19th century, the city was given the name "Stumptown" for all the logging that occurred to clear the way for farms and other development. While that name persists in popular culture, Portland now has the reputation as a "green" city, and is one of few in North America to have seen an increase in tree canopy cover even as population has grown over the past two decades (City of Portland 2017c).

Portland's history also includes racial discrimination (Gibson 2007). Racial and class inequities in the city have been found to extend to environmental hazard exposure (Stroud 1999; Fahy et al. 2019). Based on links between tree canopy extent and income, race, and other social variables in other cities, the hypothesis for this study is that Portland is not unique, and that tree canopy, like other environmental amenities, is correlated to race and class, and a reflection of disparities that exist more broadly in society. This study also seeks to build upon local findings connecting one measure of development, sewer pipe density, to other forms of green infrastructure in Portland (Baker et al. 2019).

I seek to answer the following research questions:

1. What is the spatial pattern of canopy access in Portland? Is the distribution, random, even, or clustered? Are there any hotspots or coldspots of canopy access?
2. What sociodemographic and landscape variables explain the spatial variation of canopy access?
3. Do spatial models better predict canopy access compared to non-spatial models?

2. Study Area

Portland, Oregon is located at the confluence of the Willamette and Columbia rivers in northwest Oregon and has a population (2017) of 630,331 (US Census 2019). The city is 346 km^2 in area and has a population density of 1,822 persons/km^2. Portland's cool Mediterranean climate is typified by mild, wet winters and warm, dry summers. Before European settlement began in the early 19th century, vegetation in the city included large areas of coniferous Douglas-fir/western hemlock forests as well as open deciduous forests dominated by Oregon white oak. While many central neighborhoods were fully developed by the early 20th century, large areas within Portland's current boundaries were developed later in conjunction with post-World War II population growth (Figure 2.1).

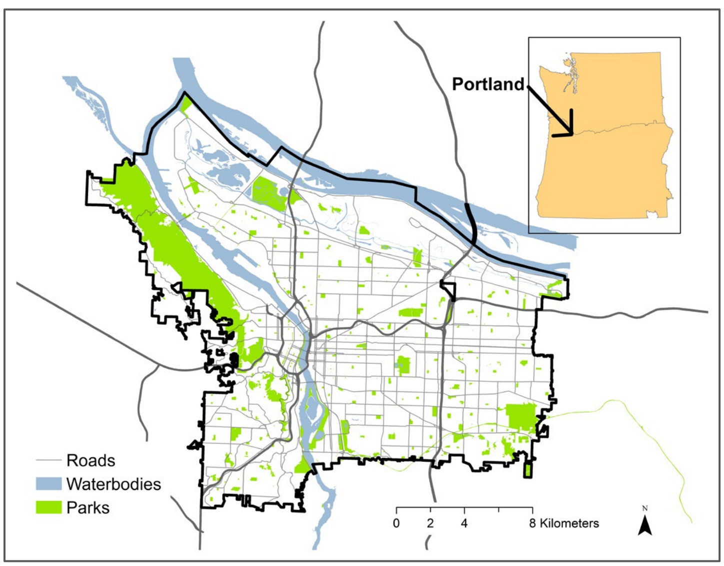

Figure 2.1 Study area: Portland, OR

Land use in the city is dominated by residential areas, which make up slightly over 50% of the city's total land area. Industrial lands, which make up 20% of the city's land area, are concentrated along the Willamette and Columbia rivers north of the central city (City of Portland Bureau of Planning and Sustainability 2018). Large forested areas make up much of the Tualatin Mountains in the western portion of the city, including Forest Park, a 21 km^2 densely forested city park, as well as natural areas on the city's east side, including Powell Butte, Kelly Butte, Rocky Butte, and Mt. Tabor.

3. Data and Methods

3.1 Data

Tree canopy data were developed by Metro from a 2014 LiDAR dataset and normalized difference vegetation index (NDVI) values derived from 2012 leaf-off six-inch color infrared orthophotos for the city of Portland (Metro 2016) and represent the two-dimensional extent of trees and their leaves, differentiated from other vegetation using a height threshold of 10 feet. This raster dataset consists of 3x3 foot cells and has a calculated overall accuracy of 90% (kappa=.78). Values for canopy access, used as the dependent variable in this analysis, were derived from this dataset (Table 2.2, and see Appendix A for methods).

Table 2.2: Data and sources

Data	**Derived variables**	**Time Period**	**Source**
Tree canopy	Canopy access (see appendix A)	2014	Metro (2016)
Socioeconomic variables	Race/ethnicity, income, education, home ownership	2011 - 2015 average	US Census American Community Survey (2016)
Sewer system	Sewer pipe density m/km^2)	2018	City of Portland Bureau of Environmental Services
Building characteristics	Building age	2018	Metro Regional Land Information System (RLIS) (2018)

Census block groups (CBGs) are the unit of analysis for this study, as it is the highest resolution spatial unit for which socioeconomic data is available, and consistent with the scale of analysis in many other studies on this topic (see Table 2.1). Census block groups do not coincide with municipal boundaries. Therefore, all block groups whose boundaries intersect the city of Portland were included in this analysis.

Socioeconomic data, including race/ethnicity, median family income, education, and home ownership are derived from the American Community Survey (ACS). The ACS is an ongoing survey conducted by the US Census Bureau, which is sent to approximately 250,000 addresses monthly and consists of a large number of questions regarding demographics, housing, and income. Each of the variables used for this study are 2011-2015 averages by census block group (US Census 2016), coinciding well with the 2014 canopy data. Race/ethnicity groups chosen for this study are African American (non-Hispanic), Asian (non-Hispanic), Hispanic, and White (non-Hispanic). These groups were chosen because they are the largest groups in the city comprising 5.7%, 7.8%, 9.7%, and 71.0% of the total population, respectively.

Tax lot data, including information on building age, were provided by the Multnomah County Assessor's Office, and accessed through Metro's Regional Land Information System (Metro 2018). Sewer system data was obtained from managers at the Portland Bureau of Environmental Services, the city's sewer and stormwater infrastructure agency.

Data representing biophysical factors were not included in this study, although it is acknowledged that soil type, soil depth, elevation, aspect, and available moisture could have an impact on long-term canopy growth. Lack of reliable data, concerning urban soils in particular, as well as the overwhelming impact of human activity on the landscape especially in regard to soil alteration and watering regimes would potentially result in unreliable findings relating canopy access to these variables.

3.2 Methods

After creating a new metric, canopy access (see appendix A for methods), this study employed regression analysis to determine which socioeconomic infrastructure-related factors most determine access to the benefits of tree canopy in Portland, OR. Ten independent variables were chosen based on their association with canopy cover in previous studies of environmental equity and urban forests (see Table 2.3 below for a list of variables used in exploratory and spatial regression analyses). Canopy access values were aggregated to the census block group (CBG) level, which is the smallest spatial unit for which relevant race/ethnicity and socioeconomic data are available, and a common unit of study in urban natural resources research (e.g. Chang, Parandvash, and Shandas 2010; Breyer, Chang, and Parandvash 2012).

3.2.1 GIS

All independent variables were normalized to CBG scale and were input into an ordinary least squares (OLS) exploratory regression analysis in ArcMap 10.3.1, using canopy access as the dependent variable. This analysis produced multiple models each with a different number and combination of one to ten independent variables. Models were assessed taking into account variable significance, R^2, Akaike information criterion (AIC) values, and Variance Inflation Factor (VIF). The best performing model, consisting of the five variables was chosen for the final model, showed no conflicts due to multicollinearity, with all VIF values ranging between 1.2 and 3.3.

Table 2.3: Descriptive statistics for input data

	Census block groups (n=442)			
	Min	Max	Mean	SD
Average canopy access (%)	5.2	85.2	26.7	12.2
% African American (non-Hispanic)[a]	0.0	39.8	6.0	6.9
% Asian (non-Hispanic)	0.0	28.0	6.5	4.7
% Hispanic	0.0	41.4	8.5	6.3
% White (non-Hispanic)	37.7	95.0	77.8	11.8
% Owner occupied	0.0	100.0	57.2	24.5
Median family income (2016 adjusted dollars)[a]	0.0	205,278	62,286	30,445
Percent higher education[a]	0.0	88.4	47.5	21.5
Population density (persons/km^2)	0.0	22,922	3,242	2,239
Sewer pipe density (m/km^2) [a]	282.8	72,983	31,028	10,657
Average building age (years) [a]	14	153.4	74.4	19.7

[a] Included in final model

3.2.2 Spatial regression analysis

Spatial autocorrelation can present problems when analyzing correlations among spatial datasets (Talen and Anselin 1998). These problems arise from the spatial clustering of data; values at nearby locations having relationships to values at nearby locations, either significantly more similar to or different from an expected random distribution. This spatial dependence can cause residuals to be spatially correlated, which is a violation of the assumption in regression analysis that errors be uncorrelated. Therefore, this study compares the results of an ordinary least squares (OLS) regression with those of spatial error and spatial lag regressions, which account for spatial dependence using a queen contiguity weight matrix.

The remaining five variables chosen as members of the strongest OLS model included mean building age, median household income, higher education attainment, percent African American, and sewer pipe density. These explanatory variables were then included in a spatial lag and spatial error model in GeoDa 1.12.1.161 (Anselin, Syabri, and Kho 2006). These models provide improved certainty of relationships found when using spatial data. Spatial statistical methods can be successful at detecting spatial dependence and provide regression models that account for spatial error and provide an improved fit.

4. Results

4.1 Spatial pattern of canopy access

The dependent variable in this study, canopy access, is not distributed equally within Portland. Moran's I cluster analysis (I=.76, p=0.00) revealed patterns of high canopy access in CBGs associated with natural areas and more forested southwest Portland (Figure 2.2).

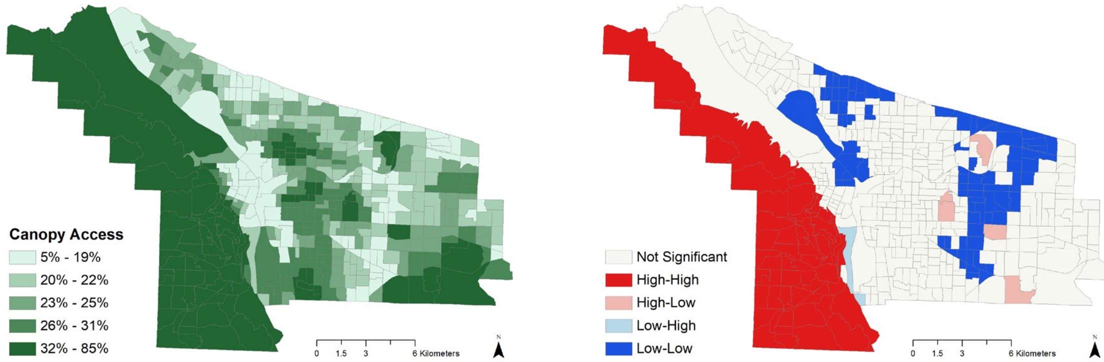

Figure 2.2: Canopy access distribution (left) and clustering (univariate Moran's I) of census block groups by canopy access (right)

4.2 Factors affecting spatial patterns of canopy access

The strongest OLS model included five independent variables and had the highest R^2 (0.54) and AIC (-933.73) values of any model. Residual error values from OLS regression exhibited significant global Moran's I statistics (I=0.45, p=0.00), underscoring the need for a spatial approach (Figure 2.3).

Spatial lag regression results in a more robust canopy model with higher R^2 (0.83) and AIC value (-1307.92) than either the OLS or spatial error model, with OLS performing the worst of the three (Table 2.4).

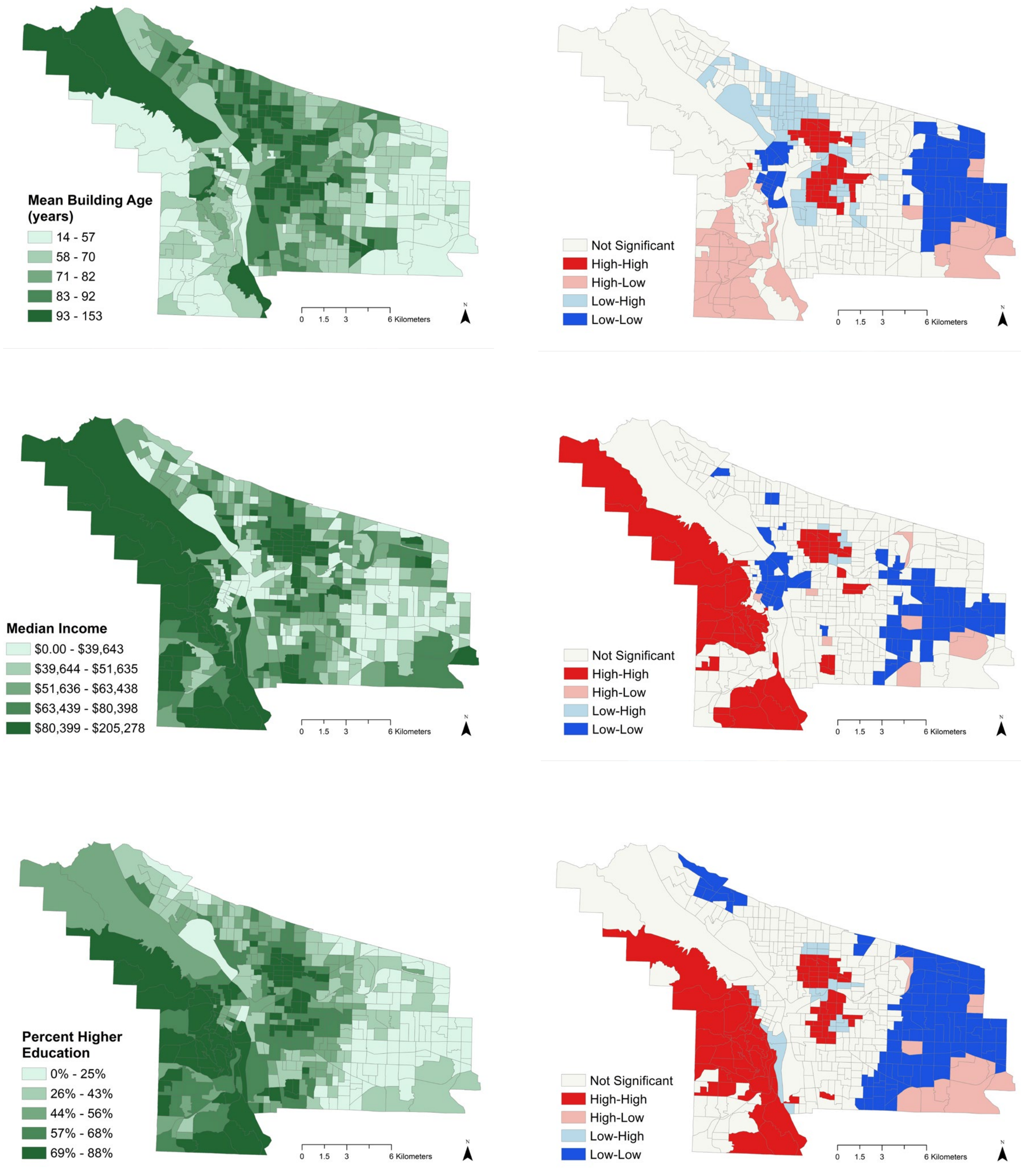

Figure 2.3: Distribution (left) and spatial clustering (bivariate local Moran’s I, right) of canopy access and independent variables

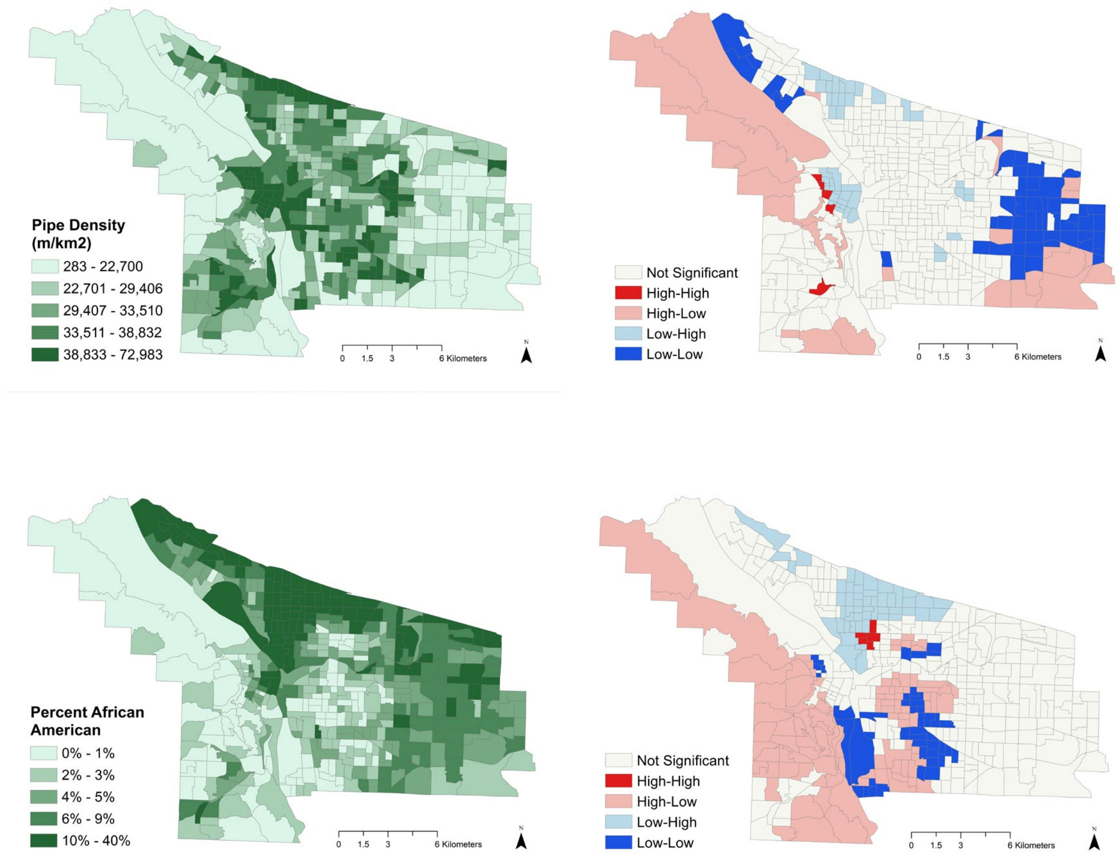

Figure 2.3, continued

Within the best performing spatial lag model, three variables had significant associations with canopy access. Two socioeconomic variables, median income and percent higher education, each had strongly significant positive relationships with canopy access ($p<0.01$), and one infrastructure-related variable, sewer pipe density, had a strongly significant negative relationship ($p<0.01$). Of all variables, median income had the strongest relationship with canopy access, followed by sewer pipe density and percent higher education. For each of these variables, relationships were significant and consistent across all models.

Building age and percent African American did not have significant associations with canopy access in the spatial lag model, although both were found to be significant (negative) in the OLS model. Notably, in the spatial error model, building age was found to have a significantly positive relationship with canopy access.

Table 2.4: Results of OLS, spatial lag, and spatial error models for Portland census block groups (n=442)

Variable	OLS		Lag		Error	
Building age	-0.14	***	0.02		0.10	***
Median income	0.37	***	0.16	***	0.17	***
Percent higher education	0.32	***	0.08	***	0.12	***
Sewer pipe density	-0.30	***	-0.15	***	-0.19	***
% African American	-0.12	***	-0.04		-0.03	
ρ	-		*0.78*			
λ	-				*0.90*	
Breusch-Pagan	*117.54*	***	*188.87*	***	*191.33*	***
Log Likelihood	*472.86*		*660.96*		*650.66*	
AIC	*-933.73*		*-1307.92*		*-1289.33*	
R^2	*0.54*		*0.83*		*0.83*	

** p<0.05 ***p<0.01. ρ=lag coefficient spatial lag model. λ=lag coefficient spatial error model. AIC=Akaike information criterion

5. Discussion

5.1 Determinants of canopy access in Portland

Findings in this study support other research that broadly associates social stratification and economic advantage with access to the ecosystem services provided by urban vegetation.

Median family income is strongly positively associated with Portland's canopy cover. This finding is consistent with other studies around the world that have linked higher wealth to higher rates of canopy cover and green space in Brazil (Pedlowski et al. 2002), Australia (Shanahan et al. 2014), Canada (Greene, Robinson, and Millward 2018), and the United States (Iverson and Cook 2000; Landry and Chakraborty 2009; Cowett 2014). The rate of higher education attainment is also significantly and positively associated with canopy access in Portland, which mirrors other findings in Indiana cities (Heynen and Lindsey 2003) and Providence, Rhode Island (Cowett 2014).

The only other variable found to have significant association with canopy access, sewer pipe density, was also the only variable with a significantly negative relationship. This finding points to a negative relationship between tree canopy and the level of development, however it is notable that population density did not also prove to have the same explanatory power. Possible other explanations could include pipes taking up soil volume otherwise available for trees, or maintenance and construction of sewer-related infrastructure resulting in tree removal, which would have a long-term negative impact on tree canopy. More research is needed to better understand the relationship between development and tree canopy in Portland. However, these mixed results are hopeful, in that population density need not necessarily mean lower rates of access to canopy. In fact, between 2000 and 2015, tree canopy citywide increased in spite of population growth of nearly ten percent over the same period (City of Portland 2017c). With population in the Portland area expected to grow 50% by 2035 (Armstrong and Williams 2013), continued efforts to support low-impact development and consideration of urban forest impacts of new development will ensure that population growth in Portland does not result in large losses of tree canopy.

While the proportion of non-white racial and ethnic groups has been found to be negatively correlated to urban canopy in Tampa, FL (Landry and Chakraborty 2009), Miami, FL (Flocks et al. 2011), and New York, Baltimore, and Philadelphia (Schwarz et al. 2015), these variables do not explain canopy distribution in the city of Portland. Variables representing whites, Asians, and Hispanics showed no significance and were therefore excluded from the spatial models. While percent African American was significant and negatively associated with canopy access in the OLS model, it did not reach significance in the spatial models. By some measures, Portland is less segregated than other cities where relationships between tree canopy and race/ethnicity have been found, with a low overall population of non-white racial and ethnic communities compared to other major U.S. cities (Brown University 2019). This may explain the lack of explanatory power found with these variables in this study.

Variables associated with housing did not prove to have significant relationships with tree canopy in this study. Rates of owner occupied housing were not significantly associated with tree canopy as in other cities (e.g. Perkins, Heynen, and Wilson 2004; Landry and Chakraborty 2009). This variable was hypothesized to have a positive relationship with canopy cover for multiple reasons: first, wealth and home ownership have been found to be significantly and positively related (e.g Perkins, Heynen, and Wilson 2004). If income is a significant predictor of access to tree canopy, presumably home ownership would follow the same pattern. Secondly, land management regimes in owner-occupied spaces could feature more investment in trees, which can take decades to grow to add to the tree canopy. The cost of this investment might, however, be exactly what dissuades home owners from tree planting in the first place, especially in rights-of-way, where in Portland the City retains ownership of trees, but property owners bear the responsibility (and costs) for their care and maintenance. In research on participation in a Portland tree planting program, Donovan and Mills (2014) found that the longer residents had lived in their house, the less likely they are to plant street and yard trees. This was consistent with a trend found in Sacramento (Summit and McPherson 1998) where tree planting was found to decline over a resident's tenure. Home ownership, therefore, has potentially mixed effects on tree canopy cover.

While the building age did show significant explanatory power in both the OLS and spatial error models (although, notably, in different directions), in the strongest model building age did not have significant relationship with tree canopy. This variable seems to be very tied to a city's particular development pattern and history. While researchers in Indiana and the Peel Region of Ontario found housing age to be positively associated with tree canopy (Heynen and Lindsey 2003; Conway and Bourne 2013), a study of an older city, Montreal, Canada found the opposite relationship, where more canopy was associated with newer housing (Pham et al. 2012). In Portland, housing west of the Willamette River, especially in the more expensive hilltop areas, is relatively new, built after the 1960s. These are also some of the most forested neighborhoods in the city, some reaching over 50% canopy cover. East of the Willamette River, which was mostly cleared farmland at the beginning of the 20th century, patterns of tree canopy more closely follow the model of younger cities where the oldest neighborhoods developed prior to World War II feature more canopy simply because the trees have had more time to grow.

5.2 Model performance, limitations, and areas of future study

This study used spatial regression methods to identify relationships between socioeconomic and landscape variables with tree canopy. Results indicate that these spatially explicit models outperform traditional OLS regression techniques, adding to the growing body of work that these types of data are best studied with these more nuanced methods (e.g. Schwarz et al. 2015). While outside the scope of this study, multilevel modeling is one such more nuanced method that not only accounts for the spatial autocorrelation of these data, but also provides insight into how relationships between variables are working across space (Locke et al. 2016). Despite the fact that this study finds race and canopy access to not be significantly related, local models may show that relationships vary across space, and may be significant in some areas.

The citywide approach taken here is valuable, but further study could restrict analysis to certain target geographies in order to test whether relationships may vary. A focus on residential zones would mitigate any effect that commercial and industrial spaces, which generally have much less tree canopy, have on the results of this work. Additionally, while population density is not found to be a significant predictor of canopy access here, exploring the relationships between canopy and certain housing types (single-family, multi-family, high-density residential) that dominate different residential zones could yield different results. Finally, as new canopy data becomes available, tracking how changes in canopy access may result in changes in its relationship to the independent variables used in this study over time would be valuable.

6. Conclusions

This study examined the spatial pattern of tree canopy cover in Portland, OR and used spatial statistics to examine sociodemographic and other determinants of access to this resource. Both distribution and statistical analysis show that in Portland, the strongest positive associations with canopy access are median income and higher education attainment. This provides a picture of economic advantage leading to greater enjoyment of the services trees provide, reinforcing other forms of advantage, including physical and mental health outcomes, school success, and public safety—advantages that are often less present within communities of color. While the percent of African Americans did not reach significance, it was close (significant at $p<0.1$) and consistently negative across all models. This would indicate that a focus on areas with larger populations of non-white residents would serve communities not currently receiving an equitable share of the benefits of tree canopy. The strongest negative association with canopy access found was with density of sewer pipe infrastructure, demonstrating a negative link between development and the ability to sustain tree canopy.

While spatial models are widely accepted for these types of studies, the more spatially explicit metric of tree canopy used here should be considered for use in other cities. Spatial regression accounts for spatial dependence of data, however a model is as only good as the data going into it. In this case, aggregating urban tree canopy to spatial units as large as neighborhoods or census block groups creates inaccuracy due to the arbitrary nature of those boundaries. Research shows the benefits to humans that tree canopy provides are leaky, spreading relatively far away from where they are produced (e.g. Netusil, Chattopadhyay, and Kovacs 2010; Donovan et al. 2011). When trying to find a human relationship with tree canopy, scientists are investigating ecosystem services that expand beyond the boundaries of tree canopy itself. The moving window approach developed in this study is a better measure of how humans benefit from urban trees and provides a more accurate metric for use in regression analysis.

Should cities stop setting goals for tree canopy cover, and instead write canopy access into their plans? Probably not. Goals and metrics need to be easily understood by the public, and relatively easy to measure. Because of this, canopy access should remain an object of academic study, where it will provide a clearer picture of what drives human relationships with urban trees.

It is clear that outside of “people with means find a way to live near trees,” this and other studies show that there are no consistent relationships between demographic, infrastructure, and other variables with tree canopy in cities across the world. Cities all have particular histories and politics, which can be harder to measure but potentially have more power over the urban landscape than the variables chosen in this study. Recent research has called for a more historically explicit approach to how we understand urban forests around the globe, which has particular lessons for management of these resources (Roman et al. 2018).

III. Canopy Potential and Ecosystem Services in Portland, OR

1. Introduction

The benefits of trees as tools for everything from environmental and public health improvement to drivers of economic activity and improvements in public safety in cities are well documented (See Table 3.1, and Wolf 2018). In acknowledgment of the benefits of urban trees, cities across the world cite the areal extent of tree canopy cover as a key metric of ecosystem health and human well-being (e.g. City of Toronto 2013; Government of the District of Columbia 2013; City of Melbourne 2014). Whereas improved human physical and mental health outcomes, air and water quality, or other environmental indicators can be difficult to track or communicate to the public, tree canopy cover provides a relatively simple metric that cities have identified as encompassing general progress towards these goals (City of Portland 2015a; Davey Resource Group 2015).

Early on in municipal canopy goal setting, many cities followed general guidelines put out by a U.S. based non-profit, American Forests, stating that 40% canopy cover was the optimal extent universally, regardless of climate, and some cities still adhere to this advice despite the non-profit having since disavowed the number (American Forests 2017). Beginning in the first decade of the 21st century, researchers began to propose targets based not on a universal standard, but rather on the amount of available land for expanding canopy extent, referred to as canopy potential, and to measurable outcomes in associated ecosystem services (Grove et al. 2006; Mcpherson et al. 2008). However, the studies that produced these targets were expensive and used methods out of reach of most municipalities because they required computationally intensive land cover classification, and in some cases automated assessment of individual site potential (Wu, Xiao, and McPherson 2008).

Table 3.1: Summary of selected research on ecosystem services of urban trees

Benefit found	**Author**	**Year**	**Study Area**	**Ecosystem services quantified monetarily?**
Air quality improvement	Rao et al.	2014	Portland, USA	Yes
	Escobedo and Nowak	2009	Santiago, Chile	No
	Morani et al.	2011	New York, USA	No
Carbon sequestration	Nowak et al.	2013	Multiple cities, USA	Yes
Reduced stormwater volume	Xiao et al.	1998	Sacramento, USA	No
	Berland et al.	2017	n/a	No
Urban heat mitigation	Akbari, Pomerantz, and Taha	2001	Los Angeles, USA	Yes
	U.S. Environmental Protection Agency	2008	n/a	No
Energy savings	Akbari et al.	1997	Sacramento, USA	Yes
	Sawka et al.	2013	Sacramento, USA	Yes
	Wang et al.	2016	Phoenix, USA	Yes
Increased property values	Tyrväinen	1997	Joensuu, Finland	Yes
	Mansfield et al.	2005	North Carolina, USA	Yes
	Donovan and Butry	2010	Portland, USA	Yes
	Netusil, Chattopadhyay, and Kovacs	2010	Portland, USA	Yes
Human health	Lovasi et al.	2008	New York, USA	No
	Donovan et al.	2013	Multiple cities, USA	No

Advances in technology, including increased availability of Light Detection and Ranging (LiDAR) data and high-resolution photography, have enabled researchers to produce fine scaled land cover datasets capable of remotely identifying discrete planting locations. At the same time, improved tools for estimating the ecosystem services provided by urban forests, notably i-Tree developed by the US Forest Service (US Forest Service 2017), have made it possible to link existing and potential canopy to quantifiable benefits (see Table 3.2).

Recent research has used improved tools and high resolution datasets to identify the capacity to expand the urban forest and estimate the resulting ecosystem services produced by this expansion in terms of urban heat reduction (McPherson et al. 2013), air quality improvement (Bodnaruk et al. 2017), energy consumption (Skelhorn, Levermore, and Lindley 2016), and public health (Locke et al. 2010; Rao et al. 2014). The capacity of urban forests to provide provisioning ecosystem services of food and fuel have also been explored (Davies et al. 2017).

Table 3.2: Selected studies of canopy potential and ecosystem services

Author	**Year**	**Study Area**	**Size (km^2)**	**Existing Canopy Cover**	**Additional Canopy Potential**	**Ecosystem Services ($1M)**
AMEC	2011	Salem, USA	158	18%	45%	14.2
O'Neil-Dunne	2012	New York, USA	736	21%	43%	n/a
McPherson et al.	2013	Metro Denver, USA	1867	16%	35%	900
Xiao et al.	2013	San Jose, USA	391	15%	20%	321
City of Toronto	2013	Toronto, CAN	630	28%	42%	n/a
Bodnaruk et al.	2017	Baltimore, USA	239	24%	21%	6.3 (ozone and $PM_{2.5}$ only

Along with technological advances, more standardized methods for identifying canopy potential have also taken shape (University of Vermont Spatial Analysis Laboratory 2019; US Forest Service 2019). Led by researchers associated with the US Forest Service, protocols have been developed for which land covers are included in canopy potential, and how it is measured (O'Neil-Dunne 2012b). However, due to differences in land use, land cover, and the particular histories of how city boundaries get drawn, assessments of canopy potential and its associated ecosystem services vary widely from city to city. These assessments are important in setting tree canopy goals supported by local data.

Portland's tree canopy goal of 33.3% first appeared in a 2007 report which cited a prior Urban Forestry Management Plan (2004) that had set goals for different land uses based on outside experience; American Forest's recommendations, regulations from other cities, and conversations with urban forest researchers (City of Portland 2007). The 2007 report also cites a canopy assessment from 2002 that found 26% citywide canopy cover. Taken together, the goal of one-third canopy cover was set and subsequently given a timeline to achieve by 2030 in the Climate Action Plan (City of Portland 2009). Despite multiple new assessments of canopy cover and fine-scaled land cover data that have been produced since this report, this goal has not been revisited. This study will provide updated information on the land use and land cover in Portland, opportunities and constraints to expanding canopy cover in the city, and a valuation of the ecosystem services that would result from meeting increased canopy cover targets.

In this chapter, I seek to answer the following research questions:

1. Given Portland's current land use assemblage, what is the realizable, or market, potential area for canopy growth, given known social preferences and biophysical constraints, and how does this canopy potential vary across space?
2. What is the value of ecosystem services that this canopy potential represents?
3. What are the urban forest management implications of these findings?

2. Study Area

The City of Portland, Oregon is the largest in the state, with a population of 630,331 (2017). It serves as the center of a metropolitan area of approximately two million residents (Figure 3.1). The city is 346 km^2 in area and has a population density of 1,822 persons/km^2. Part of the maritime Pacific Northwest, Portland's climate is characteristically mild with pronounced wet and dry seasons, supporting forested ecosystems where urban areas do not encroach. The mean annual temperature is 12.5 degrees Celsius and annual precipitation is 91 cm, 90 percent of which falls between the months of October and May (National Weather Service 2019).

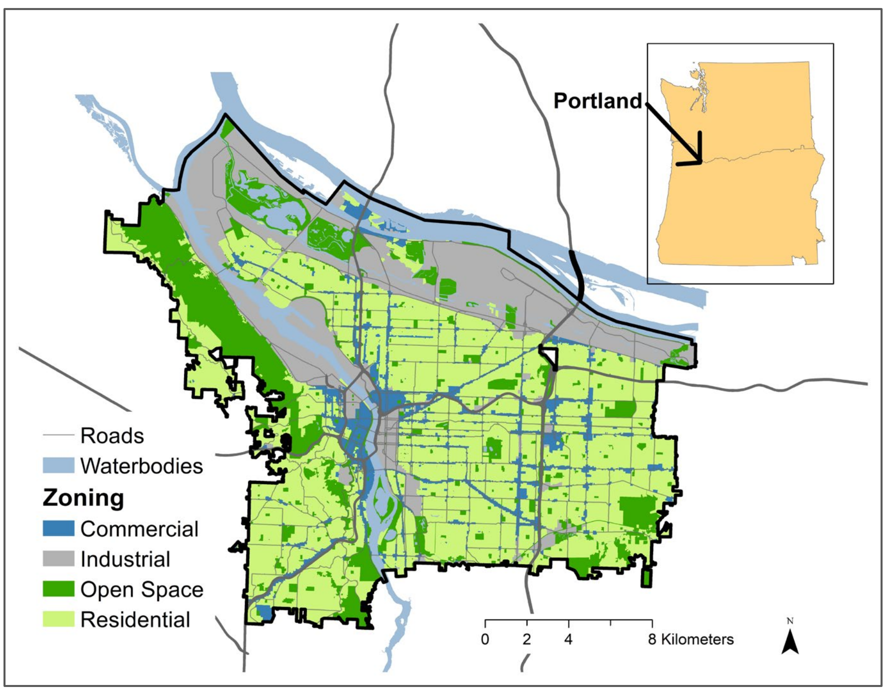

Figure 3.1 Study area: Portland, OR, with zoning categories (2018)

Residential areas make up slightly over 50% of the city's total land area, with industrial lands concentrated along the Willamette and Columbia rivers north of the central city covering 20% of the city's land area (City of Portland Bureau of Planning and

Sustainability 2018). Large forested areas make up much of the Tualatin Mountains in the western portion of the city, as well as natural areas on the city's east side. City-owned natural areas cover almost 10 percent of the city's area (32 km^2), with Forest Park, located on the city's northwest side, making up more than half of this total (Portland Parks & Recreation 2018).

European settlement in the 19th century led to development near the downtown core throughout the first half of the 20th century. Development of residential areas in what is now East Portland (east of 82nd Ave) and west of the Willamette River largely occurred post-World War II. Portland has grown in area due to a series of annexations beginning in the 1890's, lasting up to the late 20th century. Most of East Portland, comprising over a quarter of the city's total area, was annexed into the city between 1980 and 1995. Having been developed under a variety of regulatory regimes including building codes and state-mandated planning for urban areas, patterns of land use and development are inconsistent across the city.

3. Data and Methods

3.1 Data

Tree canopy data was developed by Metro from a 2014 LiDAR dataset and NDVI values derived from 2012 leaf-off six-inch color infrared orthophotos (Table 3.3, Metro 2016). This raster dataset consists of 3x3 foot cells and has a calculated overall accuracy of 90% (kappa=.78).

Table 3.3: Data and sources

Data	Time Period	Source
Canopy	2014	Metro (2016)
Waterbodies	2018	Metro RLIS (2018)
Zoning	2018	City of Portland (2018)
Impervious surfaces	2014	City of Portland, BES (2016)
PDX primary zone	2014	Port of Portland
Buildable Lands Inventory (BLI)	2015	City of Portland, BPS (2015)

Impervious surface data was provided by the City of Portland, Bureau of Environmental Services. This dataset categorized impervious surfaces into buildings, parking lots, and streets.

Due to potential wildlife conflicts, trees are managed differently around airports due to federal regulation, and have thus been exempted from a number of potential canopy studies (AMEC 2011a; NCDC 2009). This is true in Portland as well, where within a specific zone around Portland International Airport, land use managers are exempt from City of Portland regulations regarding landscaping and from permitting under Title 11—Trees (Port of Portland 2009). This "primary zone" including the airport and surrounding areas is therefore excluded from analysis.

Finally, the Buildable Lands Inventory (City of Portland Bureau of Planning and Sustainability 2015) identifies vacant and underutilized lots in Portland that are expected to be developed, given market demand. Updated inventory of these lands is mandated as part of statewide land use regulations and provides a valuable look into where increased growth and development has the potential to impact current tree canopy. These lands make up approximately 15 percent of Portland's land area. However, not all lands are equally probable to be developed due to a number of constraints. A significant proportion of the land in the BLI is identified as "severely constrained," with questionable development potential, however, this analysis did not attempt to classify potential according to this categorization, as it is not well-defined by the agency.

3.2 Methods

3.2.1 Using GIS to identify Gross Potential Canopy

This analysis is based on existing land cover classifications, including a map of tree canopy cover derived from the 2014 Metro Regional Land Information System (RLIS) land cover classification as well as other land cover datasets maintained by the City of Portland (See Table 3.3 for data sources). Using these data within ArcMap 10.3.1 (ESRI 2014), land cover across the city was grouped into four categories: 1) water, 2) existing tree canopy cover, 3) impervious surfaces, and 4) pervious surfaces, including non-tree vegetation. Impervious surfaces were further divided into buildings, streets, sidewalks, and parking lots in order to capture differences in their ability to support tree canopy.

Those land covers not able to support tree canopy—streets, buildings, and waterbodies—were then removed from analysis. While exceptions exist, these areas cannot be planted without significant expense or redesign. Because of federal regulation of vegetation around airports, the "primary zone" around Portland International Airport (PDX) was also excluded from analysis.

Finally, areas of existing tree canopy were removed from analysis as they do not represent areas of potential. While future tree planting efforts could take place in some of these spaces, planting would not result in a notable net gain of tree canopy cover over time.

While some studies have excluded various landcovers such as parking lots and golf courses (AMEC 2011a; McPherson et al. 2013) from potential canopy estimates, I chose to include each because Portland has specific forest management policies for each of these areas (City of Portland 2004), and, in the case of parking lots, standards for tree planting when development occurs (City of Portland 2015b). Therefore, it is reasonable to include these areas as places where canopy expansion could potentially occur.

All remaining areas, including all pervious surfaces, non-tree vegetation, sidewalks, and parking lots were preliminarily classified as areas of canopy potential (Figure 3.2), able to support tree canopy and adding to the city's existing tree canopy cover. Note that areas of potential identified in this analysis are areas where it is assumed that there is enough planting opportunity nearby to support 100% tree canopy coverage—not that a tree can be planted anywhere in this space. For example, while tree planting space is limited in sidewalks, there is enough planting opportunity both within the sidewalk and on adjacent lands that trees planted may be able to create a continuous canopy over these areas. While this is also true to a lesser extent with streets (canopy currently covers 10-15% of Portland's streets), to be conservative, streets were excluded as areas of potential with no canopy assumed to be added over these spaces from additional tree plantings. See Table 3.4 for a summary of areas classified as canopy potential.

Figure 3.2: Classifying canopy potential. Areas not covered by water, buildings, streets, or existing canopy are classified as canopy potential (in orange here) prior to the application of adjustment factors.

This process resulted in the Gross Potential Canopy (GPC) for the city, or the maximum potential canopy coverage for the city, regardless of social preference. By definition, GPC estimates do not consider the presence of or preference for open natural ecosystems such as oak savanna, or diverse land uses that occur on pervious areas in cities, such as sports fields and vegetable gardens. GPC estimates consider all pervious areas and parking lots as having the potential to support continuous tree canopy. While the resulting GPC estimate will seem unrealistically high in any urban area, it is a valuable first step in potential canopy analysis and serves as a baseline for considering urban canopy coverage expansion.

Table 3.4: Land covers and canopy potential (numbers do not add to 100% due to overlap)

Potential		No Potential	
Land cover	***Percent of Portland area***	***Land cover***	***Percent of Portland area***
Pervious surfaces	28.9	Areas under tree canopy cover	29.9
Parking lots	8.8	Buildings	13.0
Sidewalks and driveways	2.0	Water	8.1
		Streets	10.4
		PDX primary zone	2.6

3.2.2 Adjustment factors and Market Potential Canopy

Urban areas, Portland included, host a diverse set of land uses and some limitations not easily identified from aerial images will necessarily preclude planting in areas of potential canopy. Creating a more realistic estimate of the full extent of tree canopy that the city can support requires a method of reducing gross canopy potential based on expected patterns of land use. The result is the market potential canopy (MPC) for the city. This study applies adjustment factors to account for sports fields, vegetable gardens, underground utilities, and other physical limitations to planting. Developing local adjustment factors for Portland would require extensive field study with randomized plots across the city, cataloging the number and types of limits to tree planting. This research would be valuable for future development of Portland's urban forest management policy; however, it is outside the scope of this project. Instead, an adjustment factor developed for a similar study in San Jose, CA (Xiao et al. 2013), which has a similar population density to Portland (US Census 2019), is used as a model for this report. That study found 64% of unirrigated, bare soil and dry vegetation to be free of such limitations; therefore, an adjustment factor of 0.64 was applied to pervious areas of gross potential canopy in Portland. While the same study found 83% of irrigated grass to be plantable, the more conservative number was applied in this research as land cover data did not distinguish between irrigated/non-irrigated in Portland, and irrigated areas are not common in the city.

Surface parking lots are included as potential in this study because of the opportunity for trees to mitigate the increased stormwater runoff and urban heating associated with these areas. Portland city code requires tree planting with the development of new parking lots (City of Portland 2015b). Although there is no set canopy goal associated with these requirements, it is estimated that current standards would lead to 35% canopy coverage of parking lots at maturity (City of Portland 2017a, and personal email communication with Susan Ellis, Senior Land Use Planner, City of Porltand Bureau of Development Services, 12/18/2017). Therefore, an adjustment factor of 0.35 was applied to all areas of potential canopy over surface parking lots.

3.2.3 Ecosystem services provided by increased canopy cover

Ecosystem service totals were estimated both annually and over a 20-year period, which follows the window for Portland's long-range planning document, the *2035 Comprehensive Plan*, and a reasonable amount of time for a tree to reach mature size (City of Portland 2016).

This study uses algorithms developed by the US Forest Service to quantify the value of air quality improvement, stormwater reduction, and carbon sequestration that meeting some or all of Portland’s canopy potential would generate (US Forest Service 2017). Additionally, aesthetic and other benefits are estimated based on local and national research on the sales prices of properties with and without trees (Anderson and Cordell 1988; Donovan and Butry 2010). These data are a proxy for the price that the public is willing to pay to live near trees and enjoy their harder-to-quantify services, including beautification, noise reduction, privacy, wildlife habitat, and psychological well-being, a finding that has been confirmed in Portland at multiple scales (Netusil, Chattopadhyay, and Kovacs 2010).

The value of environmental ecosystem services provided by a tree is based on the leaf surface area of that tree, which varies species to species. The aesthetic and other benefits of trees have been found to rely on the placement of that tree in relation to streets, buildings, and other infrastructure (Troy, Grove, and O’Neil-Dunne 2012). To calculate any of the services chosen in this study in line with the knowledge that tree species and tree placement dictate the quantity of these services, area of MPC was converted to a total number of trees that it represented by dividing by the estimated canopy area of each tree at 20 years. In calculating the aesthetic and other services provided by canopy potential, numbers of trees were attributed to specific zoning types as well as their placement on public right-of-way or private land. The species of tree chosen on which to base calculations was the medium-sized broadleaf deciduous Norway maple; a well-studied tree, and the most common street tree in Portland (City of Portland 2017a). Canopy extent of this tree at 20 years is estimated to be 30 feet in diameter based on research in nearby Longview, WA (McPherson et al. 2002).

Benefit calculations assume no net change in existing tree canopy, attributing all canopy increases to the planting of 1.5” diameter Norway maples. Ecosystem service totals are based on the annual services that trees would provide over 20 years of growth (McPherson et al. 2002). Aesthetic and other benefits are based on Portland’s median home value as of December 20, 2017 (Zillow 2017). For a full summary of values used in this study, see Table 3.5. For more information on methods in calculating these values, see Appendix B.

3.2.4 Target geographies

Geography, land use, and property ownership can each help to explain the presence or absence of tree canopy in an urban environment, as well as the limitations to the planting and preservation of trees. Using a classified map of tree canopy makes it relatively easy to analyze the data according to a number of geographies and determine the extent to which each contains tree canopy and potential. This study reports canopy and potential according to geography (east or west of the Willamette River), zoning (commercial, industrial, open space, or residential), and ownership (public, private, right-of-way).

Table 3.5: Ecosystem service values (see Appendix B for information on methods of valuation)

Service Type	**Service Value**	**Unit**	**Source**
Environmental Services			US Forest Service 2017
Air quality improvement			
O_3	$2.40	lb.	
VOC	$6.65	lb.	
NO_2	$2.40	lb.	
SO_2	$1.00	lb.	
PM_{10}	$2.72	lb.	
Carbon	$0.01762	lb.	
Stormwater	$0.02779	gallon	
Aesthetic/Other Services			
low density residential ROW	$495.15	tree	(Donovan and Butry 2010)
low density res. Non-ROW	$101.70	tree	(Donovan and Butry 2010)
all other zones	$58.10	tree	(Anderson and Cordell 1988; US Forest Service 2017)

Existing canopy and potential was also calculated across lands identified in the Buildable Lands Inventory (City of Portland Bureau of Planning and Sustainability 2015) in order to estimate an amount of canopy and potential at risk due to future development in the city (see Figure 3.3). These lands make up approximately 15 percent of Portland's land area, however not all lands are equally probable to be developed due to a number of constraints. A significant proportion of the land identified in the BLI is defined as "severely constrained," with questionable development potential, however, this analysis did not attempt to classify potential according to this categorization.

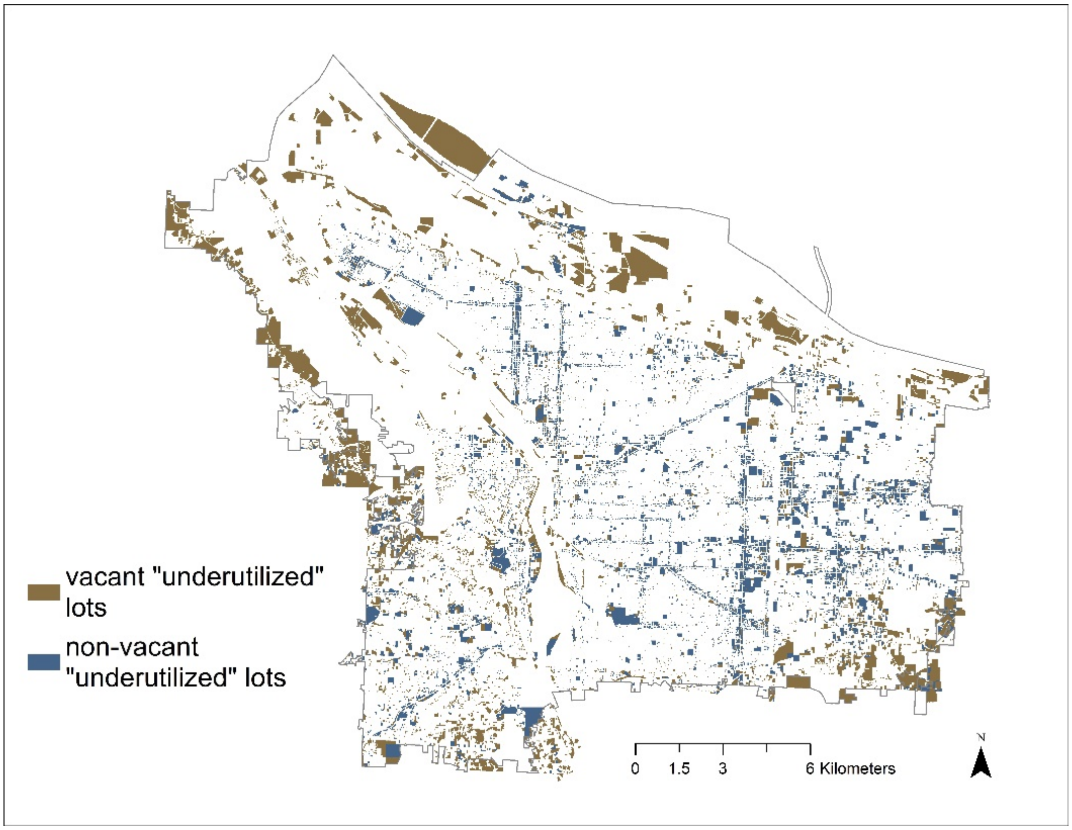

Figure 3.3: Buildable Lands Inventory (City of Portland Bureau of Planning and Sustainability 2015)

4. Results

4.1 Existing and potential canopy cover

Given current land use and development, Portland's GPC is 35,974 acres, comprising 38.8% of the total area of the city (92,680 acres). After applying adjustment factors, this study finds that Portland's MPC is 20,886 acres, comprising 22.5% of Portland's total area. Combined with existing canopy (29.9%), total canopy potential is 52.4% (Figure 3.4). Canopy potential is unequally distributed across geography, zoning

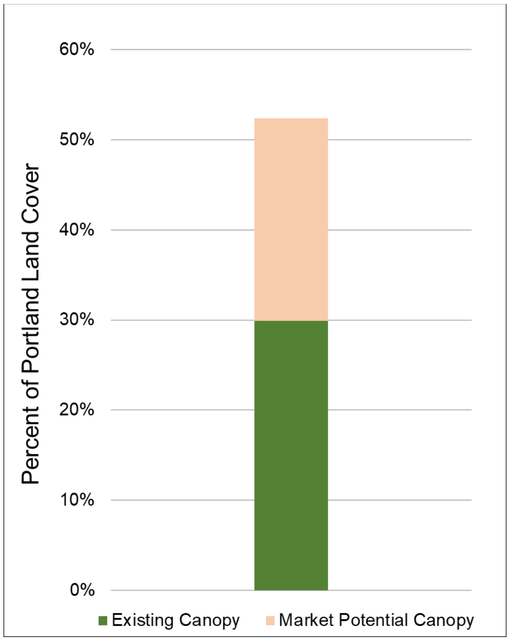

Figure 3.4: Existing canopy and potential total 52.4% of Portland land cover

class, and ownership. Portland's existing and potential canopy is broken down by target geographies below.

Lands east of the Willamette River in Portland contain 17,205 acres of MPC, comprising 82.4% of the city's overall total. Portland's west side contains 3,681 acres of MPC, comprising 17.6% of the city's overall total (Table 3.6). Within east side lands, MPC varies considerably across space, with greater amounts in north and outer east side areas (see Figure 3.5).

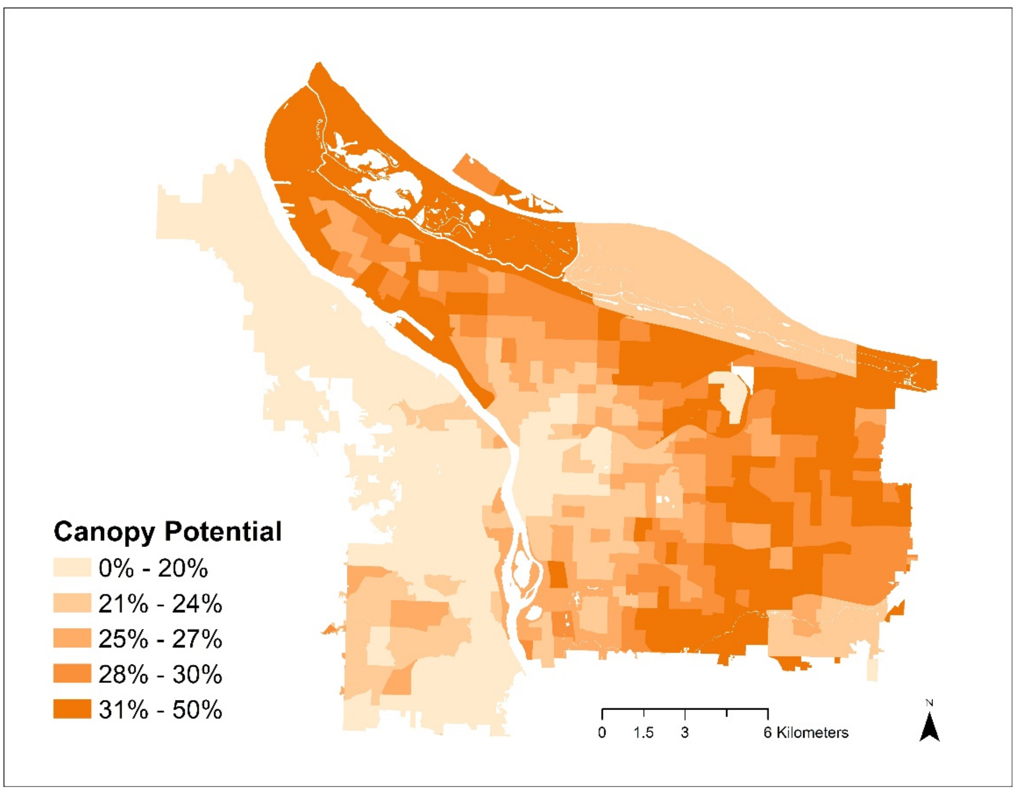

Figure 3.5: Canopy potential (MPC) in Portland census block groups, as proportion of land area

Residential zones contain the majority (53.9%) of Portland's MPC. Industrial zones contain 24.8% of Portland's MPC, and open space and commercial zones contain 13.8% and 7.3% of Portland's MPC, respectively (Table 3.6). See Appendix B for an explanation of zoning categories. Proportions of land area identified as MPC varied across zones, ranging from 18.4% of total area in open space zones to 29.2% of industrial zones (Table 3.6). Total canopy potential, including existing canopy and MPC, ranged from 35.8% in commercial zones to 82.1% percent in open space zones.

Citywide, MPC is predominantly located on privately-owned lands, which contain 62.2% of MPC compared to public lands and rights-of-way, which hold 21.1% and 16.1%, respectively (Table 3.6).

Table 3.6: Existing and potential canopy, by geography, zoning class, and property ownership

	Percent of Total City Area	**Percent Canopy Cover (acres)**	**Percent of Portland Canopy**	**Acres of Market Potential Canopy (MPC)**	**Percent of Portland MPC**
Geography					
East	72.0	20.5 (13,661)	49.3	17,205	82.4
West	28.0	54.2 (14,053)	50.7	3,681	17.6
Zoning					
Commercial	7.9	13.0 (877)	3.2	1,534	7.3
Industrial	20.8	8.5 (1,516)	5.5	5,182	24.8
Open Space	18.3	63.7 (10,001)	36.1	2,888	13.8
Residential	53.1	33.5 (15,242)	55.0	11,267	53.9
Ownership					
Public	24.5	46.9 (9,775)	35.3	4,416	21.1
Private	56.1	29.0 (13,853)	50.0	12,987	62.2
ROW	19.4	22.2 (3,674)	13.3	3,353	16.1

4.2 Ecosystem services of increased canopy

This analysis identifies 20,886 acres of MPC in Portland, representing space for planting nearly 1.3 million trees. Realizing even a portion of this potential would take significant investment by the City and its residents—an investment that would yield substantial returns in the form of environmental, social, and economic benefits. The value of ecosystem services of air quality improvement, carbon capture, reduced stormwater volume, as well as aesthetic and other benefits that this increased canopy represents is included in Table 3.7 below.

Meeting Portland's full MPC would generate an estimated $198 million in services annually. The cumulative monetary value of these services over 20 years total $4 billion (in 2018 dollars). The annual and cumulative values of meeting Portland's current canopy goal of 33.3% canopy cover are $30 million and $603 million, respectively. Meeting 35%, 40%, or 50% canopy cover would net between $45 and $177 million in annual services and other benefits. See Appendix B for an explanation of how these figures were calculated.

Of the total service value of potential plantings, 86% are in the aesthetic/other category, primarily reflecting positive property value impacts which are a proxy for other, harder to quantify benefits such as improved mental and physical health and safety that buyers have been found to be willing to pay more to enjoy (see Appendix B for a review of this research). Of the remaining, 11 percent are from stormwater savings, two percent from carbon capture, and less than one percent from air quality improvement.

Table 3.7: Annual and 20-year cumulative value of meeting tree canopy goals

	33.3% goal	**35% goal**	**40% goal**	**50% goal**	**All MPC (52.4% total canopy cover)**	
Additional trees	195,971	291,161	576,731	1,147,872	1,287,123	
Annual Services						**per tree**
Air quality	$109,743	$163,050	$322,969	$642,808	$720,789	$0.56
Carbon capture	$548,717	$815,251	$1,614,847	$3,214,041	$3,603,944	$2.80
Stormwater	$3,441,242	$5,112,790	$10,127,400	$20,156,631	$22,601,876	$17.56
Aesthetic/other	$26,073,811	$38,738,893	$76,733,892	$152,723,972	$171,251,281	$133.05
Total	*$30,173,514*	*$44,829,984*	*$88,799,108*	*$176,737,452*	*$198,177,889*	*$153.97*
20-year cumulative	*$603,470,287*	*$896,599,681*	*$1,775,982,170*	*$3,534,749,046*	*$3,963,557,775*	*$3,079*

4.3 Accounting for future development

Analysis of existing and potential canopy on developable lands identified in the Buildable Lands Inventory (BLI) shows that 19.5% of Portland's MPC lies inside these areas (Table 3.8). However, existing canopy cover on these lands is relatively high, at 42.5% for currently vacant lots and 22.5% for non-vacant "underutilized" lots totaling approximately one-sixth of Portland's existing tree canopy. Due to the fact that much of the canopy and potential identified on lands identified as "severely constrained," this should be seen as a high-end estimate of risk of canopy loss to development.

Table 3.8: Existing canopy and potential on Buildable Lands Inventory land

	Percent of Total City Area	**Percent Canopy Cover (acres)**	**Percent of Portland's Existing Canopy**	**Acres of Market Potential Canopy (MPC)**	**Percent of Portland MPC**
Vacant lots	8.6	42.5 (3,369)	12.2	2,469	11.8
Non-vacant "underutilized" lots	6.1	22.5 (1,278)	4.6	1,613	7.7

5. Discussion

5.1 Extent and distribution of potential canopy

Portland has considerable area for expanding tree canopy and its associated ecosystem services, amounting to space for nearly 1.3 million trees. This is not altogether surprising for a city that, despite having an urban growth boundary designed to promote density instead of sprawl, has relatively low population density when compared to other large U.S. cities, less dense than Buffalo, NY, Louisville, KY, or Dallas, TX (US Census 2019). Much of Portland's far east side as well areas west of the Willamette River are typified by low density single-family, suburban housing developments. The eastern sections of the city were suburbs until they were annexed by Portland in the 1980s and 1990s.

The majority of Portland's canopy and potential lies on private, residential lands, with the vast majority (over 80%) of potential in areas east of the Willamette River. These findings show that constraints to canopy expansion across the city are largely not a result of existing infrastructure (roads, buildings, etc.), which is consistent with studies of canopy potential in cities with similar development patterns (AMEC 2011c, 2011b; McPherson et al. 2013). Outside of the downtown core and most central eastside neighborhoods, which are the most built-up areas of the city, space is plentiful across zones, and mainly constrained by existing canopy.

In addition to providing a baseline estimate of canopy potential given current land use in Portland, this study includes analysis of the amount of canopy and potential on lands expected to be developed over the next 20 years. While it is uncertain what amount of BLI lands will be developed, the approach in this project was to be inclusive of all BLI lands, regardless of constraints, resulting in a baseline high-end estimate of the amount of canopy and potential at risk due to development. This study finds that over 80% of Portland's MPC lies outside of BLI lands—an encouraging sign for long-term canopy growth. Despite a common argument that there is not room for both more tree canopy and the increased housing needed to accommodate the hundreds of thousands of new residents Portland expects over coming decades, this study finds that to be a false choice.

Illustrating this fact, from 2000 to2015, Portland added over 100,000 residents while at the same time increasing tree canopy cover by from 27.3% to 30.7% (City of

Portland 2017c) (Figure 3.6). This trend is rare among cities—a much more common driver for canopy increase cited by research is population *decrease* due to landscape abandonment (Nowak and Greenfield 2012).

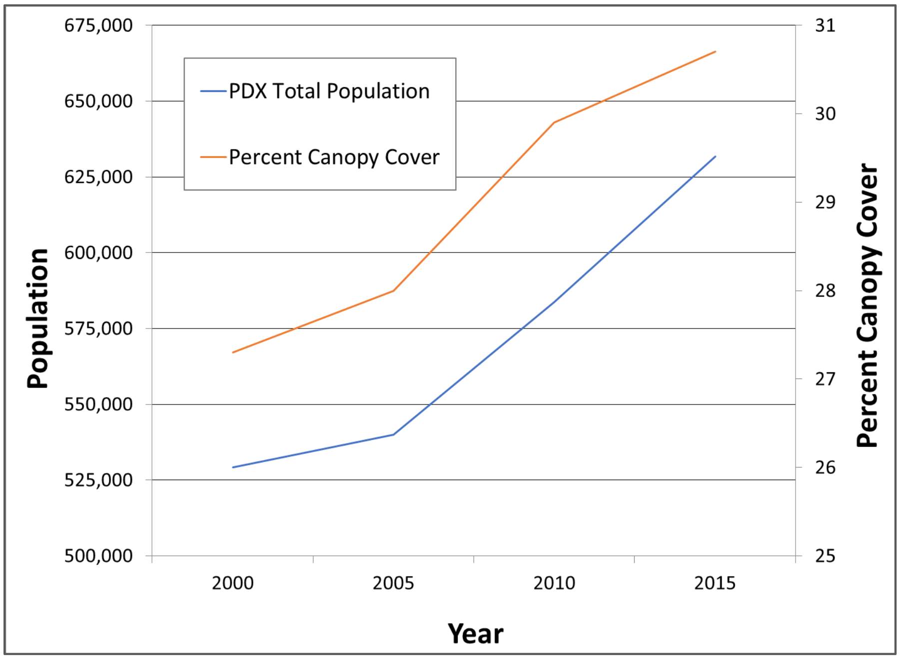

Figure 3.6: Population and tree canopy in Portland, OR, 2000-2015

5.2 Ecosystem service value of potential canopy

The value of expanding Portland's urban forest to meet some or all of its current potential is considerable, amounting to \$600 million to \$4 billion over 20 years. The largest service, providing up to \$171 million annually, is for projected property value increases, reflecting difficult to quantify benefits of urban tree canopy that residents are willing to pay to live near. The average annual value of \$154 per tree is comparable to results in other cities that measured the same services (e.g. Xiao et al. 2013).

As ample planting opportunity has been identified citywide, prioritizing how and where to pursue these services will be necessary. Decision-makers making the choice to plant trees, and subsequently the services they provide, may not place the same proportionate value on the benefits as they are reported in this study, nor residents who may be more interested in maximizing services related to public health than property values (Baur et al. 2016).

5.3 Implications for urban forest management

The fact that the majority of potential canopy in Portland occurs on private lands has implications for management of the urban forest, and for strategies available to the city to expand this resource. In order to meet even its now modest canopy goal of 33.3% tree canopy, urban forest managers will have to engage property owners in education, stewardship, and tree planting opportunities, as this group currently manages the majority of land and majority of trees in the city. Neighborhoods with the highest levels of potential canopy as a proportion of total land area are clustered in Portland's far north and far east sides, which are also relatively less affluent than the rest of the city. This points to an opportunity to provide services in areas of most need.

It is promising to see that Portland has increased tree canopy while adding population, and yet still has ample canopy potential to meet and exceed its canopy goal. With few exceptions, canopy is declining in urban areas in the U.S., even in cities with much higher budgets for tree planting and maintenance (Nowak and Greenfield 2018). Whether or not Portland can continue this trend is unclear, and this study does not attempt to answer this question. Further study is needed to model the canopy impacts of projected growth in the city in a manner that accounts for development allowances within current zoning, code regulations and exemptions to tree planting and preservation, and incentives for building certain housing types, e.g. accessory dwelling units on single family lots.

5.4 Limitations

Findings presented here are necessarily limited to Portland's land use, geography, and pattern of development. This study adds to the growing body research in urban canopy potential, which varies widely depending on the local context. While most studies on this topic provide analysis based on current land use only, forgoing any look into future development patterns, findings in this chapter provide a useful gauge of how canopy potential will be impacted as Portland's population continues to grow. Where reliable data exists, analysis of canopy potential in other cities should follow. Further study with more refined modeling of Portland's future development would provide insight into those potential canopy impacts and their effect at multiple scales.

Ecosystem service values are reported at the citywide scale only. I made this choice for multiple reasons. First, the ecosystem service analysis is focused on Portland's citywide canopy goal, and the potential benefits that could result from meeting or exceeding 33.3% canopy cover. While canopy potential is reported according to geography, zoning, and ownership, ecosystem services were not analyzed at this scale. Further study of ES at a finer resolution could provide valuable information for urban forest managers in deciding where to prioritize investments in tree planting.

However, study of ecosystem services at a finer scale would require reconsideration of the methods used here and in other cities. Service values are highly dependent on housing prices, which are related to many other factors, including access to transportation corridors, schools, and other amenities (Li et al. 2016). Basing local service values on local housing prices would undervalue trees in less expensive areas related to service values in higher-priced zones. The environmental justice impact of this is important, as it could lead decision-makers to prioritize planting in high-income areas, reinforcing existing inequalities. Also, there is evidence that the marginal value of trees can be inversely related to canopy cover in some cases, especially in high-canopy zones. In one Portland study, increases in tree canopy in heavily treed neighborhoods actually *decreased* sales prices of homes (Netusil, Chattopadhyay, and Kovacs 2010). Cooling, stormwater capture, air pollution mitigation, and other services likely follow similar patterns. More study on this effect is needed before a fine scale analysis of ecosystem services can be completed.

While the major constraint on canopy potential in the majority of the city is the amount of existing canopy cover, investments in planting should not assume that this always the case and focus only on those areas of greater potential. This study does not recommend specific areas to prioritize investments in tree canopy expansion. However, urban forest managers should use the findings of this study and those of Chapter 2 to prioritize areas of low canopy access and low-income in conjunction with relative amounts of canopy potential. Strategies used in high priority planting areas will depend on the amount and distribution of canopy potential.

6. Conclusions

This study identifies considerable space for expansion of Portland's tree canopy, after taking into account social preferences and development forecasts. While this potential is not distributed equally across the city, it is clustered in lower-canopy and lower-income CBGs, which provides an opportunity for increasing equity in ecosystem service provision in precisely the communities where it is lacking.

These findings fill a gap in the knowledge about the patterns of canopy potential in Portland and the varying constraints to that potential across the city. Urban forest managers can use this study to tailor strategies for tree planting based on relative amounts of, and constraints to, potential canopy in a given area. For instance, while the majority of canopy potential occurs on private, residential properties citywide, there are a small number of areas, mainly in the central city, where a higher proportion of potential is on public properties and rights-of-way. While many of the former areas would fall into a "low canopy/high potential" category, neighborhoods in the latter would more likely be categorized as "low canopy/low potential" zones. Solutions for increasing canopy in these areas are different, and creating a tree canopy and potential matrix based on this analysis would support decision making.

Portland has bound itself to increase tree canopy, setting a goal of 33.3% by 2035. This study finds that this goal is easily achievable, given the amount of available land and the trajectory of canopy extent over the past 15 years. This goal is also modest, given the amount of space that exists for potential tree planting and growth. Achieving this goal would mean expanding Portland's tree canopy by just 15% of the total canopy potential (MPC) identified in this analysis.

The benefits of a more ambitious target are considerable and measurable. Meeting a 40% canopy goal, for instance, would mean nearly doubling the ecosystem services generated by meeting the current 33.3% goal, an addition of $575 million in services over

20 years. Researchers have shown that dollars are not the only measure of service, finding that Portland's trees are also saving lives (Rao et al. 2014). As tools of increasing public health and mitigating the impacts of climate change, be it increased urban heating, more intense rain events, increased stream temperatures, or worsened air quality, trees are singular in their effectiveness, and require a remarkably small investment when compared to other forms of infrastructure. For this reason, the city should consider increasing its tree canopy goal as part of an overall strategy of addressing public health and climate change in the future.

IV. Conclusions

The goal of this project was to characterize the distribution of Portland's tree canopy, potential for expansion of that resource, and the resulting ecosystem services. This research fills a gap in local knowledge about the urban forest and the sociodemographic and other drivers that shape it. Studies around the world have shown the extreme variability in the extent and distribution of tree canopy in cities, and in who enjoys the services that those trees provide. The information presented in these chapters provides useful decision support for managers overseeing efforts to expand the urban forest equitably.

In the first chapter, I presented results of the creation of a novel, spatially explicit metric of canopy coverage and spatial regression analysis to answer the following questions: what is the spatial pattern of canopy access in Portland? What sociodemographic and landscape variables explain the spatial variation of canopy access, and do spatial models better predict those variables' impact on canopy access compared to non-spatial models?

In the second chapter, I analyze the realizable potential canopy coverage for the city, based on current land use assemblage, social preferences, and biophysical constraints, and estimate the ecosystem services under multiple scenarios fulfilling some or all of that potential, answering the following questions: what is the realizable, or market, potential area for canopy growth in Portland, given known social preferences and biophysical constraints, and how does this canopy potential vary across space? What is the value of ecosystem services that this canopy potential represents, and what are the urban forest management implications of these findings?

The results of this research reveal an urban forest that is not evenly or equitably distributed, with variables representing economic advantage and level of infrastructure development best explaining this distribution. The environmental justice implications of these findings are twofold: 1) in Portland, as in many other cities, the lowest-income residents do not have access to an equal level of services provided by the urban forest, and 2) as development occurs, especially in areas of East Portland, there is a danger of losing canopy in neighborhoods that hold a disproportionate amount of low-income communities of color. Portland's recent history suggests that canopy can continue to expand as population grows, but it is unclear whether this is a sustainable trend, and whether its dynamics are analogous at the local scale.

In general, the opportunity for increasing the services of urban canopy in Portland is considerable, especially in areas currently lacking trees, as is the value of realizing some or all of those services. Taken together, the results in these chapters show that the prospect of adopting a "level of service" model to canopy expansion efforts could be an effective way for urban forest managers to acknowledge current inequities, quantify the impact of that imbalance, and justify efforts to undo it. The urban forest is a municipal asset, and the extent to which this asset is providing an unequal level of service to residents is a metric around which investments could be prioritized.

Urban forest managers will have to consider the potential for this investment to exacerbate inequity. Large-scale tree planting efforts often ignore or fail to track environmental justice-related outcomes (Locke and Grove 2016; Garrison 2018), and in cases where those outcomes are built in to the program, they may not match the priorities of the residents they seek to serve (Carmichael and McDonough 2018). While disinvestment has been a source of environmental inequity in cities around the world, investments in those same neighborhoods can be threatening for their power, either real or perceived, to spur gentrification and displacement.

This project is limited in its scope, serving as a case study and adding to the body of literature around determinants of tree canopy and other environmental amenities, urban environmental justice, tree canopy potential, and ecosystem services. Promising areas of further research that could add to these findings are discussed including use of local regression models, modeling future development and its impact on potential tree canopy, and finer scale estimation of ecosystem services of proposed tree plantings.

Understanding the local dynamics which work to both drive and constrain the extent and distribution of ecosystem services in urban areas is important for setting metrics of success for natural resource management. I recommend that the City of Portland uses the information presented here to revise current tree canopy goals, both citywide and at finer scales aimed at addressing inequities in the ecosystem services provided by Portland's urban forest.

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Appendix A: Development of a Novel Measurement of Urban Canopy, *Canopy Access*

1. Introduction

Studies of urban tree canopy commonly utilize land cover data to assess the proportion of a city under tree canopy cover. This global value provides a baseline, and the process is then repeated for sub-areas of a city or region (e.g. neighborhood, council district, watershed) in order to examine the spatial distribution of tree canopy. As high-resolution land cover data becomes more readily available, an increasing number of cities and metropolitan areas are carrying out these canopy assessments (O'Neil-Dunne 2012a; City of Hartford 2014; City of Seattle 2016).

There is good reason for a city to inventory canopy cover area within its jurisdiction; canopy data can inform natural resource and urban planning strategies and aid in analysis of how citywide policies influence canopy cover over time. This value is non-spatial; while a city (or region) may have 40% canopy cover, this number gives no indication of how that canopy is distributed. Therefore, knowing citywide canopy cover does not provide much help to urban forestry managers looking to target tree planting efforts towards lower canopy areas within a city. One common method of determining how tree canopy is distributed within a city or region is to break canopy cover data down to a smaller scale, such as neighborhood, council district, or watershed. While watershed-scale analysis could aid in natural resource planning and water quality improvement efforts, using more artificial political or administrative boundaries can lead to distorted conclusions regarding how residents benefit from canopy cover within a city.

The modifiable areal unit problem (MAUP) is a concept well-established in academic literature, but little acknowledged outside geography. As Openshaw and Taylor (1979) describe, summary values (such as proportion of canopy cover within an area) will be influenced by the aggregation of spatial data into areal units. In this case, a canopy value for a given point on a map will change, often dramatically, depending on the area (e.g. neighborhood, census tract, postal code) within which canopy cover has been aggregated. The endlessly "modifiable" nature of drawing arbitrary lines on a map allow a researcher to choose an equally endless number of values from which to make conclusions.

A second and related problem also occurs when making conclusions about the benefits of tree canopy coverage, and how those benefits are enjoyed by urban residents. Following a larger trend within natural resources research, studies in urban forestry are increasingly interested in quantifying the ecosystem services, or human benefits, of the urban forest. In Portland, efforts have been made to acknowledge inequities in access to these benefits, and programs are in place to mitigate these inequities through planting and outreach. As with canopy coverage, any effort to map ecosystem services will necessarily entail aggregation, and therefore be susceptible to MAUP. Additionally, canopy benefits do not necessarily occur at the neighborhood scale or stop at neighborhood boundaries. One can imagine a resident who lives on the border between "high" and "low" canopy neighborhoods; not only will a map of canopy coverage place that household in a high canopy or low canopy zone depending on which side of the line it happens to fall, the benefits of nearby canopy on the other side of that line, be it temperature moderation, housing price effects, or air quality improvement, will not extend beyond that boundary on a map, despite the enjoyment of those benefits on each side.

In the context of urban forest management seeking to maximize the production of ecosystem services from urban trees, a measurement which reflects the way these benefits are distributed across space and experienced by urban residents will result in more informed action towards expanding these services for the most public benefit. This study creates a new metric with which to measure tree canopy in urban areas, *canopy access*, which includes all canopy within a given distance of a spatial unit, thereby negating the impact of MAUP and creating a more realistic picture of how tree canopy and its benefits are distributed and enjoyed within a city.

2. Methods

To calculate canopy access, I first created a grid of 100m cells over the extent of the study area, including all cells that intersect the Portland city boundary. The 100m spatial unit represents a compromise between the need for high-resolution data for analysis and the limited computing power available. Using the 100m grid resulted in 38,532 cells across the city, each cell covering approximately half of a typical city block in Portland, which range from 50-75m in width by 100-200m in length. While decreasing cell size would yield a more detailed picture of canopy access, it would also greatly increase the necessary computations for calculating canopy extent (for instance, using a 50m spatial unit would result in over 150,000 cells across the study area).

I then created a ¼ mile (402m) circular buffer from the centroid of each cell, resulting in an overlapping series of circular polygons each with a radius of ¼ mile (see figure 4.1). While the various benefits of tree canopy operate at multiple scales, the ¼ mile buffer choice is based on the extent of impact that Netusil, Chattopadhyay, and Kovacs (2010) found that increased canopy has on housing prices in Portland, OR. This represents one extent that canopy benefits have been proven to flow within this study area, therefore the significance of results reported in Chapter 2 are limited by this choice.

I then calculated percent canopy coverage for each buffer and attributed those values back to their corresponding 100m cell. All analysis was conducted with ArcGIS 10.3.1 (ESRI 2014) with the exception of calculating canopy within overlapping polygons, for which I used Geospatial Modelling Environment (Beyer 2012). Canopy data used for this study extends beyond Portland's boundary, therefore canopy access values for cells whose buffers extend outside of Portland included canopy outside of the city and were not susceptible to edge effects.

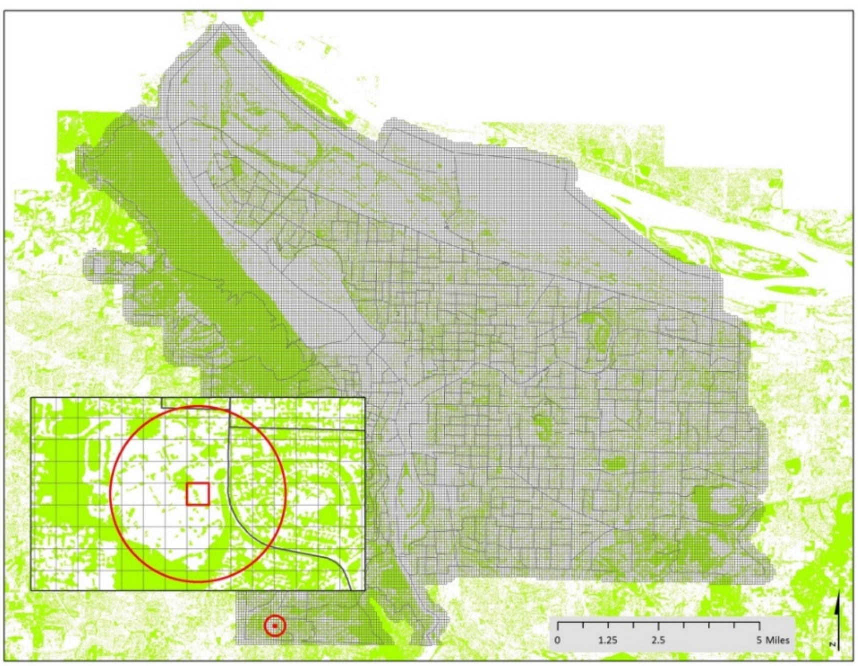

Figure 4.1: Canopy access calculations were made using a 100m grid, values for each pixel being the canopy cover for all areas within a 1/4 mile of its center.

3. Results and Discussion

The resulting map of canopy access created by this process provides a more detailed picture of canopy than those made from aggregating tree canopy cover to the neighborhood or block group scale (see figure 4.2 below). Because the ecosystem services provided by tree canopy do not stop at administrative boundaries, this map of canopy access also more clearly shows the gradient of services that flow from larger forested areas.

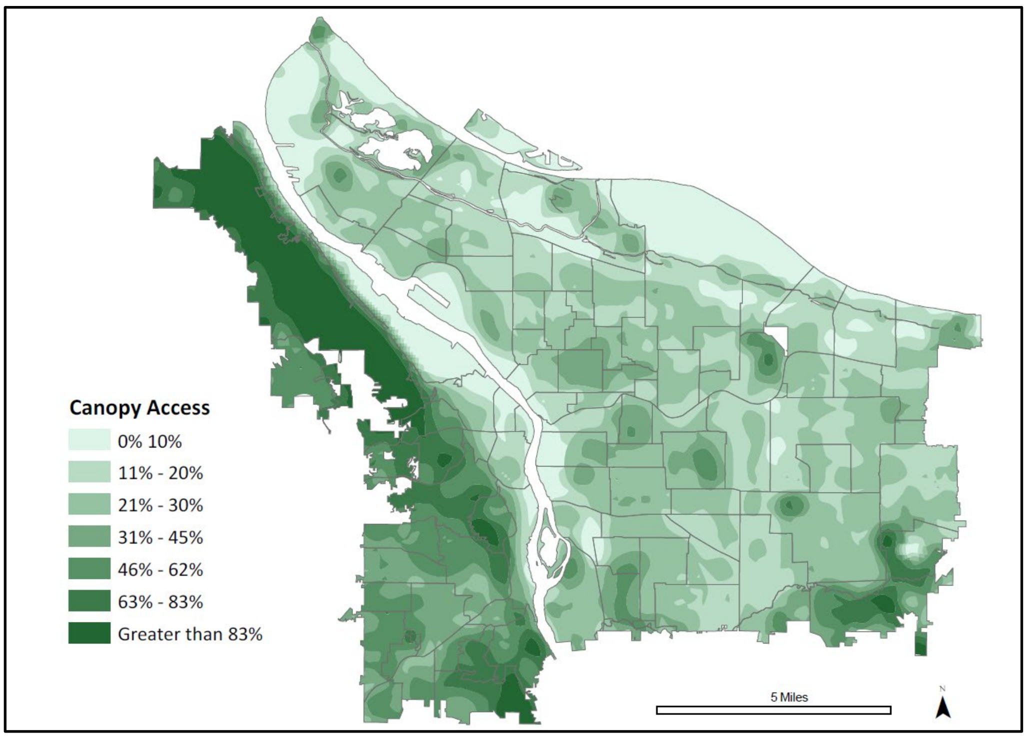

Figure 4.2: Map of canopy access in Portland

With this information, prioritizing of tree planting activities can focus on areas that receive the fewest services of the urban forest, not simply those which happen to fall within a district that includes treeless areas. One example of this is the famously tree-lined Ladd's Addition, which falls in Portland's Hosford-Abernethy neighborhood. This neighborhood also happens to include a large industrial area with low canopy cover, which gives it one of the lowest rates of canopy cover of any neighborhood in the city. Despite this, Ladd's Addition residents enjoy cool shade and other benefits under their canopy of elm trees. Those elms also provide benefits outside of the square, which canopy access also accounts for.

One possible avenue for putting this research to use is to integrate canopy access and canopy potential to pinpoint the highest priority planting sites in Portland. These datasets could also be combined with social or demographic data, which would be potentially valuable for decisionmakers with multiple objectives.

Appendix B: Methods and Resources for Valuing Ecosystem Services of Urban Trees

Environmental services

Air Quality

Trees intercept and absorb air pollutants on their leaf surfaces. Their ability to do so is based on tree size and species, which together determine total leaf surface area. The average yearly monetary value of the removal of ozone, nitrogen dioxide, sulfur dioxide, and particulate matter less than 10 microns (PM_{10}) were calculated based on hourly deposition rates, pollutant concentrations, and meteorological data for a regional reference city (McPherson et al. 2002) and current prices (Hirabayashi 2016), using a common medium sized tree, Norway maple, as a model for potential plantings. Net calculated air quality benefits were reduced to account for estimated annual emissions of biogenic volatile organic compounds (BVOCs).

Carbon Sequestration

Trees store carbon from the atmosphere in their biomass, which has the effect of reducing overall atmospheric carbon dioxide, a pollutant linked to global climate change. The monetary value of this service was calculated using species-based biomass equations (US Forest Service 2017) and the US government's estimate of the social cost of carbon (Interagency Working Group on Scocial Cost of Greenhouse Gases 2016).

Stormwater Reduction

Trees reduce the amount of rain that enters the stormwater system by intercepting precipitation with their foliage, which reduces water treatment costs. As with the interception of air quality pollutants, a tree's ability to provide this service is a function of its leaf surface area, with large and evergreen trees providing the most benefits.

Stormwater reductions and associated savings were calculated based on leaf area, canopy area, and water depth (Xiao et al. 2000), local meteorological data, and the avoided cost of stormwater processing (McPherson et al. 2002).

Aesthetic and other services

Aesthetic and other services were calculated as the increase in property sales price attributable to the presence of trees on site, and reported citywide. To calculate this value, the median price of a house in Portland ($405,500) was multiplied the percentage attributable to the tree, based on research, and divided by 20 to get an annual estimate based on the 20-year period used in this study.

Potential tree planting sites in rights-of-way adjoining low-density residential zones were each priced at 3% of the median home value for Portland, based on Donovan and Butry's (2010) finding that street trees contribute a 3% increase in sales price of Portland single family homes. Prices for all other potential trees were based on Anderson and Cordell's (1988) finding that mature front yard trees increase single family home sale values by 0.88%, which continues to be the standard valuation used in the i-Tree toolset (US Forest Service 2017). In order to be conservative, and to acknowledge that trees elsewhere in the yard might contribute less to overall sales price increases, reduction factors were applied to areas outside single family residential rights-of-way (Mcpherson et al. 2008). Potential planting sites in low-density residential zones outside the right-of-way were each valued at 70% of this total, and all sites in all other zones were valued at 40%. See Table 5.1 for an explanation of zoning class categories.

Table 5.1: Zoning class categorization

Commercial	Industrial	Open Space	Residential	
			Low-Density	*High-Density*
CI2 CM1 CM2 CM3 CE CR CX	EG1 EG2 EX IG1 IG2 IH	OS	RF R20 R10 R7 R5 R2.5	R3 R2 R1 RH RX IR CI1